at 40 torr, again in agreement with our observations. Qualitatively the pump pulse shows a minimum at the center similar to the measurements shown in Fig. 5c.

## DISCUSSION

The current results show that Xe is a suitable medium for third harmonic conversion of XeF radiation and that conversion is dominated by effects related to the three photon resonance enhancement. At the peak pump powers used here, of the order of $7 \times 10^{12}$ W/cm$^2$, the conversion shows evidence of limitations due to intensity dependent phase mismatches. Extension to higher pulse energies requires the use of larger focused beams and phase matched mixtures. These will best be accomplished in a static cell geometry rather than a differential pumping geometry. Ultimately the highest conversion efficiency will be obtained when the conversion is dominated by the Kerr effect, and other possible intensity dependent effects are eliminated as discussed by Zych and Young.[1] Again the situation can be assured by using longer confocal parameters lower peak intensities and phase matching mixtures. The ultimate conversion efficiency that can be obtained then depends only on the ratio of the susceptibility for harmonic generation relative to that for the Kerr effect. Experiments are underway to determine the quantities.

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# USE OF XeCl AMPLIFIERS FOR DEGENERATE FOUR-WAVE MIXING


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## ABSTRACT


The use of a laser amplifier as a Degenerate Four-Wave Mixing (DFWM) element for phase conjugation is a powerful general technique, particularly useful for UV excimer lasers. In this paper we will discuss our initial experiments, which yielded the first demonstration of DFWM in a XeCl amplifier.[1]


## INTRODUCTION

Among the many techniques for phase conjugation, DFWM in a saturable amplifier has significant advantages. By choosing the laser gain medium as the DFWM medium we have a phase conjugator automatically matched to the laser of interest. This is particularly useful for UV lasers, where high reflectivity phase conjugate media are difficult to identify. Since the phase conjugate process involves a single photon resonance, the pump requirements are low. In fact, even in comparison with DFWM in saturable absorbers, a more common technique to date, the pump requirements are predicted to be much smaller. The reflectivities are relatively high, and by using part of the media outside of the mixing region as an amplifier, the total reflectivity, as demonstrated in the experiments reported, can be very high. While the phase conjugate medium uses an active device, an already existing amplifier in an optical system may be used as the conjugator, so that no additional elements may be required.

Phase conjugation in saturable amplifiers has been previously reported using Nd:YAG,[2] $CO_2$,[3] and Cu vapor[4] lasers. These experiments were done in the laser cavity, where the pump beam intensities were relatively high. The experiments discussed here are the first reported using DFWM in an amplifier in the ultraviolet, and the first reporting phase conjugate reflectivities using any technique for the XeCl laser. The XeCl laser, with its long lifetime/fill for an excimer laser and its high efficiency when discharge pumped, is of great interest for many applications. The results of the work reported here are of interest specifically for the XeCl laser as well as its more general applicability to excimer and other laser systems.

A schematic diagram of DFWM in an amplifier is given in Figure 1. The pump beam enters the amplifier with intensity $I_1$ and the counter-propagating pump with intensity $I_2$. The latter is most simply generated by using a mirror M1 to reflect all or part of the forward pump. Because the DFWM medium considered here exhibits gain, the intensities of the pump beams increase as they traverse the cell, and in general $I_1(0) \neq I_2(L)$ unless the reflectivity of M1 is chosen appropriately. The probe beam enters the amplifier with intensity $I_3$.

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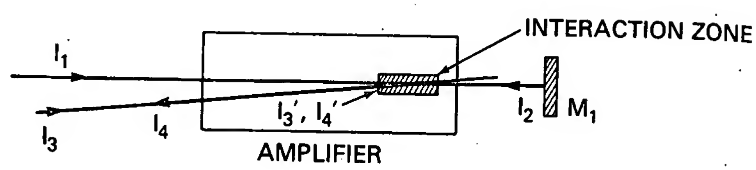



Fig. 1. Schematic diagram of degenerate four-wave mixing geometry in an amplifier.

Depending on the beam diameters and the angle between the pump beam and the probe beam, the beams will overlap and DFWM occur over the whole amplifier length or some part of it. In the latter case, it is useful to distinguish the DFWM reflectivity from the total reflectivity of the entire amplifier by defining $I_3'$ as the probe intensity after it traverses the non-interacting gain length and at the beginning of the DFWM region. The counterpropagating signal beam generated by the interaction of the other three waves has intensity $I_4' = R_N I_3'$ upon leaving the interaction region and intensity $I_4(0)$ after exiting the amplifier. The observed total reflectivity $R_t = I_4(0)/I_3(0)$ may be many orders of magnitude times $R_N$ due to the gain experienced by $I_3$ and $I_4'$, while under the proper conditions $R_N$ itself may exceed unity. A theoretical analysis of this system has been done by Reintjes and Palumbo,[5] and those results will be used for comparison with the experimental data.

## THEORETICAL RESULTS

The potential of saturable amplifiers for providing high reflectivities at low pumping powers is illustrated in Fig. 2. Here we show the total reflectivity for an amplifier with a total intensity gain of $e^8$. Each of the curves was calculated for a different length used for the nonlinear interaction, expressed as a fraction of the total length of the amplifier, with the remainder of the gain length used for amplification of the probe and conjugate waves. For these calculations the probe and generated waves were assumed to be weak compared to the pump waves. For the solid curves the reflectivity of the retroreflecting mirror used to generate the backward pump wave was unity while for the dotted curves it was 0.04.

As a function of incident pump intensity each of the curves increases at low pump intensity, peaks and then falls off for high pump intensity as the nonlinearity saturates. These results show that for the total reflectivity there is an optimum division of the amplifier into a nonlinear interaction region and a gain region. For the unity retroreflector the optimum nonlinear interaction length is about 0.12 of the total length and the maximum total reflectivity is of the order of $10^4$ ($10^6$%). For the .04 reflector the optimum nonlinear interaction length is increased to about 1/4 of the total length and the maximum reflectivity is somewhat lower, about $5 \times 10^3$.



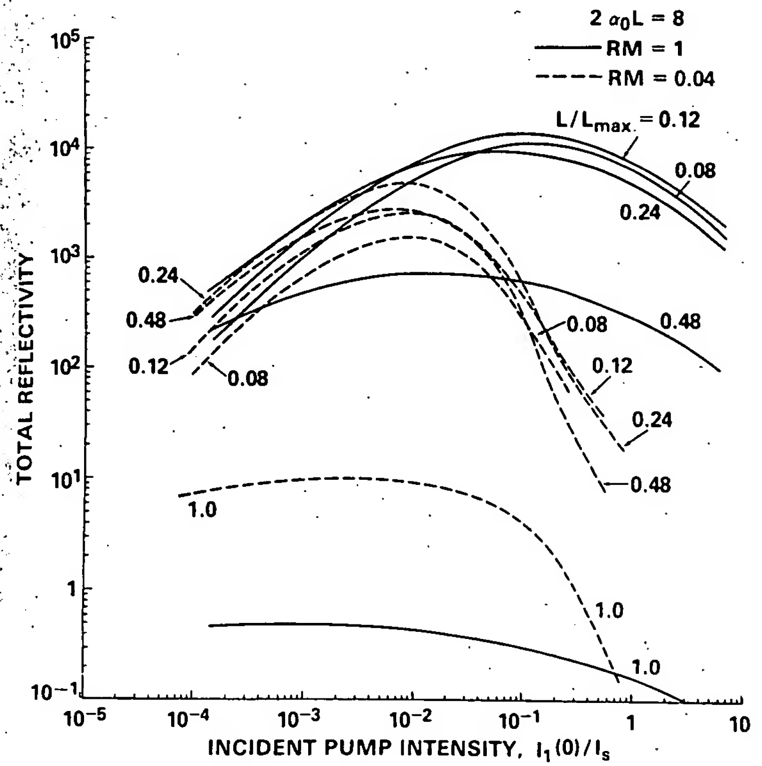
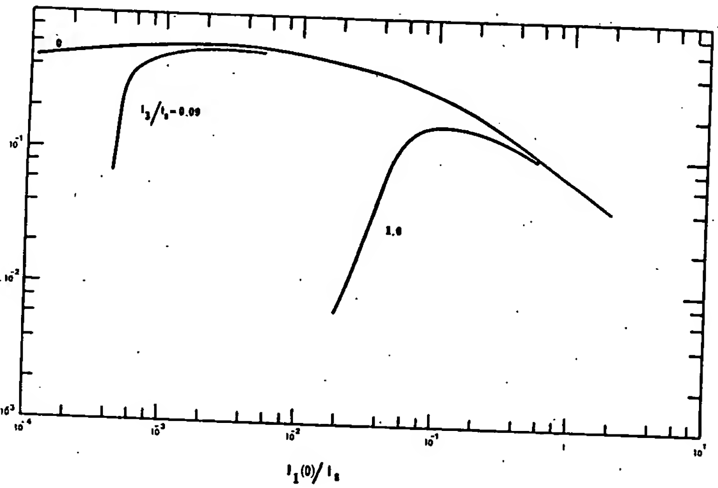



Fig. 2. Total reflectivity, including the effect of amplification outside of the nonlinear interaction region for various fractional interaction lengths and pump mirror reflectivities.

We have also examined the effects of a finite probe beam intensity on the DFWM reflectivity. For these calculations we assumed that the total amplifier length was used for the nonlinear interaction and that the two pump waves were orthogonally polarized, while the probe wave was polarized parallel to one of the pump waves and the conjugate wave was polarized parallel to the other. The reflectivity is shown in Fig. 3 for three different pump intensities, expressed as fractions of the saturation intensity.




g. 3. DFM reflectivity for orthogonal polarization for various
lues of the incident probe wave intensity.

As a function of incident pump intensity the reflectivity for a nstant incident probe intensity deviates considerably from the low eld value at low pump intensities but rapidly approaches the low eld reflectivity as the pump intensity increases. These results w that the DFWM reflectivity approaches the low field value, and erefore becomes independent of the value of the incident probe ensity, generally for incident pump intensities that are con- erably less than the incident probe intensity. As a result the tem has the potential for faithful conjugation of incident probe ensities than are larger than the incident pump intensity.

EXPERIMENTAL RESULTS

We have examined some of these predictions using the arrangement wn in Fig. 4. The pump and probe radiation was generated in a XeCl llator amplifier combination. The oscillator was operated in a ole cavity with apertures to control the spatial mode. The trum of the oscillator was reduced to a value of 0.1 $cm^{-1}$ by using ating at one end of the cavity and two intracavity etalons to sfy the linewidth requirements of the nonlinear optical inter- on. After amplification the beam carried about 20 KW in a pulse tion of 10 nsec. The amplified beam was subsequently propagated t 20 ft. and then spatially filtered to provide a high quality



beam for the pump waves. The pump wave then propagated into the amplifier through an aperture and its intensity was varied by placing filters in the pump beam before the entrance to the cell. The probe beam was obtained by reflecting 1% of the pump wave with beamsplitters BS1 and BS2 as shown in Fig. 4.

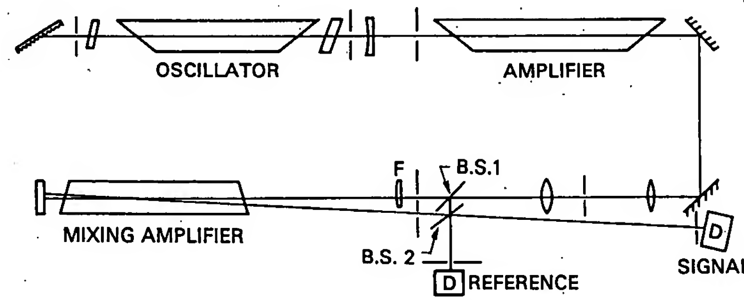



Fig. 4. Experimental arrangement for observing DFM reflectivity in XeCl.

The portion of the probe beam that passed through beamsplitter BS2 was detected with a photodiode D1 and served as the reference signal for both the incident pump intensity and the incident probe intensity. The generated signal, counterpropagating to the probe wave, passed back through BS2 and more apertures to the signal photodiode located about 10 feet away. The apertures and detectors were aligned and the system calibrated by tilting the mirror M1 to retro-reflect the probe beam with the amplifier off.

The amplifier used as the mixer was an x-ray pre-ionized XeCl discharge driven by a 100 nS transmission line. This device was chosen because of its homogeneous, stable, long pulse characteristics. The discharge aperture was 3.5 x 3.5 cm and the active length 80 cm. The pump and probe beams were measured to have a 1/e diameter of 0.16 cm, and intersected 7 cm from the end of the discharge at an angle of 23 milliradians, so that the interaction length was approximately 7 cm. The pump and probe beams therefore passed through a gain length of approximately 70 cm before entering the mixing region, while the generated beam also passed through a 70 cm gain length. This arrangement was chosen for a number of reasons. The overlap length L was within the measured coherence length of the laser source. The laser pulse widths were sufficiently short that it was desirable to minimize the time required for the pump to pass through and be reflected back through the interaction region. The long gain length for the generated beam insured that the signal would be large and easily discriminated against the spontaneous emission background. The amplifier was operated under conditions such that it did not oscillate when the mirror was aligned and the single pass gain was measured as a function of input intensity to obtain the small signal gain $g_0$ and saturation intensity $I_s$. The small signal gain was 10%/cm and the saturation intensity 1 $MW/cm^2$. The total reflectivity was determined

by measuring the signal and reference intensities as the pump intensity was changed by inserting filters at F. Additional variation in the probe and pump intensities was observed in the reference signal due to shot-to-shot variation in the laser intensity. The pump intensity was thus varied from 2 to 400 kW/cm$^2$ ($0.002I_s$ to $0.4I_s$) while the incident probe intensity varied from 2 to 4 kW/cm$^2$. The maximum total reflectivity, $R_t = I_4(0)/I_3(0)$, was measured to be 100 ($10^4$%) at an incident pump intensity of 400 kW/cm$^2$ (.4 $I_s$).

The measurements were compared with the predictions of the theory for saturable amplifiers by removing the effects of the gain on the probe and generated beams in the front part of the amplifier. In general the gains were so high that the probe wave saturated the gain in this region for both the forward probe wave and the return conjugate wave. The additional gain on both waves was calculated numerically and was used to correct the measured values to give the reflectivity due to the four-wave mixing process. These results are shown in Fig. 5. The calculated curve was determined from the numerical evaluation of the appropriate equations. For these calculations the effects of the backward grating formed by the interference of the probe beam with the backward pump wave were neglected because of the relatively large value of the atomic lifetime compared to the washout time of the grating.[5] The reflectivity calculated in this manner, shown as the dotted curve in Fig. 5 shows good qualitative agreement with the measurements, in particular reproducing the scaling with pump intensity quite well. The residual discrepancy, of the order of a factor of 2, could be due to the fact

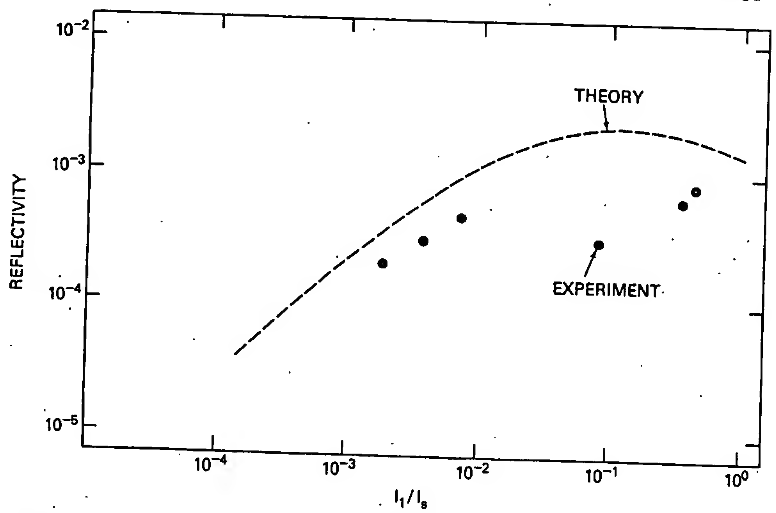



Fig. 5. Comparison of theoretical DFM reflectivity and experimental measurements, corrected for the effects of gain outside of the nonlinear interaction length.



that the probe intensity was comparable to the pump intensity at the entrance of the nonlinear gain region, while the calculations were done in the weak probe limit. Subsequent measurements are underway to determine the optimum operating conditions for the amplifiers and to evaluate the fidelity of the conjugation process especially in the large reflectivity, high intensity limit.

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